**Supplementary information for:**

# Geophysical Insights from the First Geomagnetic Field Absolute Intensity Curve for Central Asia (2200BCE – 2000CE), and Implications for Archaeomagnetic Dating

## Extensive introduction to the most important intensity features of the geomagnetic field for the last 4000 years

Archaeomagnetic studies have revealed that the intensity of the EMF has undergone significant fluctuations on multidecadal to centennial scales over the past millennia (e.g., Kovacheva et al., 2014). In Europe, two notable intensity maxima occurred during the $6^{th}$-$7^{th}$ and $8^{th}$-$9^{th}$ centuries CE, followed by a steady decline. A significant decrease in intensity has been also observed in South America over the recent centuries, linked to the expansion of South Atlantic Anomaly, one of the most prominent geomagnetic field features at Earth´s surface today. In contrast, regions such as Central Asia have experienced and increase in intensity over the past 150 years (Alken et al., 2021). Among the most remarkable EMF intensity events of the past millennia is the Levantine Iron Age Anomaly (LIAA), which occurred during the $1^{st}$ millennium BCE and is characterized by exceptionally high field intensities. Archaeomagnetic studies by Ben-Yosef et al. (2009) and Shaar et al. (2011, 2016) identified sharp increases in geomagnetic field intensity in the Levant during this period, with Virtual Axial Dipole Moment (VADM) values reaching up to 190 $Zam^2$ around 1000 BCE and 750 BCE. Similarly, high-intensities were recorded in Turkey around 1050 BCE (Ertepinar et al., 2012), further supporting the existence of the LIAA. More recently, Shaar et al. (2022) proposed that up to four distinct intensity peaks occurred during this period.

Despite these advances, several key questions regarding the origin and behavior of the LIAA remain unresolved. Some studies propose a western limit for the anomaly between 30º and 35º E (Shaar et al., 2017), while others suggest that the LIAA originated in the Levant around 1000 BCE and migrated westward, reaching Iberia by ~750 BCE (Molina-Cardín et al., 2018; Osete et al., 2020). However, recent high-quality archaeomagnetic data from the central Mediterranean do not support this migration hypothesis, instead suggesting that the LIAA emerged in the Levant and subsequently faded to the north, west, and east (Rivero-Montero, Gómez-Paccard, Kondopoulou, et al., 2021). Further complexity arises from findings in eastern China, where a potential high-intensity event has been dated to ~1300 BCE (Cai et al., 2017). This has led to speculation that it may be a precursor to the high-intensity episodes recorded in the Levant and Turkey. However, due to the scarcity of high-quality intensity data for the 2$^{nd}$ and 1$^{st}$ millennia BCE in the intervening regions, this hypothesis remains difficult to test robustly (see the GEOMAGIA.v3 global compilation, Brown et al., 2015 and Campuzano et al., 2019 for a critical reassessment of the global intensity database).

Global geomagnetic field paleoreconstrucion have linked the LIAA to a normal flux patch at the core-mantle boundary (CMB) beneath the Arabian Peninsula (Korte & Constable, 2018; Osete et al., 2020). Korte and Constable (2018) suggested that the LIAA developed and dissipated in situ. In contrast, Osete et al. (2020) proposed that the anomalous flux patch expanded northwestward, gradually weakening and reaching Iberia around 750 BCE. Their study further suggested that around 600–500 BCE, the LIAA underwent a resurgence beneath the European continent before ultimately fading. However, the analysis by Rivero-Montero et al. (2021) indicates that the VADM intensity maximum observed around 500 BCE is present across the entire European continent, from the

Canary Islands to Turkey. This widespread pattern suggests that the event was not controlled by a localized feature such as the LIAA.

To better understand the evolution of the geomagnetic field during the 2nd and 1st centuries BCE in general and the LIAA behavior in particular, it is essential to refine geomagnetic field reconstructions across the Eurasian continent. In particular, the eastern extent of the LIAA remains poorly constrained due to the scarcity of archaeomagnetic studies in Central and Southeast Asia. Furthermore, the number of high-quality archeointensity data in these regions remains significantly lower than in Europe (see Campuzano et al., 2019; Brown et al., 2015), highlighting a critical gap in our understanding of the geomagnetic field changes in this area.

To address this, our team has made an effort to study EMF changes in Uzbekistan (Bonilla-Alba et al., 2021, 2024). Previous data indicate that the EMF intensity experienced a significant decline in intensity between 400 BCE and 1 CE, followed by a rapid recovery with rates of change reaching up to −15 μT per century (Bonilla-Alba et al., 2021 and references therein). This variation has been attributed to non-dipolar sources of the geomagnetic field, particularly the presence of a reversed flux patch at the CMB beneath this region (Bonilla-Alba et al., 2024). This feature has been observed recently in India by Mohite et al. (2025). After this period, high-quality intensity data suggest that EMF intensity peaked around 800 CE before gradually decreasing in a nearly linear trend up to the 18th century (Bonilla-Alba et al., 2024; Troyano et al., 2021).

**Archaeological context and sampled pottery collections**

The Bronze Age sites Jarkutan and Molali Tepe are affiliated to the Sapalli Culture, a regional variant north of the Amu Darya River of the Oxus Civilization or Bactria-Margiana Archaeological Complex, which dates in this region from ca. 2100 to 1400 BCE (Askarov 1977; Kaniuth 2021; Lyonnet and Dubova 2021). The evolution towards the Iron Age in the area involved significant changes in settlement patterns, as well as in the social and cultural trends; the site Kuchuk Tepe is representative of this period (Askarov, Al'baum 1979).

Jarkutan (or Dzharkutan) is situated on the left bank of the Bustansaj river, approximately 60 km north of Termez (Fig. 1). Initial excavations began immediately after its discovery in 1973, led by S.R. Pidaev and V. Pilipko from the Institute of Archaeology of the Academy of Sciences of the Uzbek Soviet Socialist Republic. Several teams have since conducted archaeological excavations at the site, including local archaeologists from the Sherabad Archaeological Detachment of the Institute of Archaeology of the Academy of Sciences of the Uzbek Soviet Socialist Republic from 1973 to 1990 (Askarov 1977; Askarov and Abdullaev, 1983; Ionesov, 2002; Askarov and Shirinov, 1993; Shirinov and Baratovm 1997; Shirinov, 2002), a German-Uzbek team from 1994 until the early 2000s (Huff, 2000), the French-Uzbek "MAFOuz-Protohistoire" expedition between 2007 and 2014 (Bendezu-Sarmiento and Mustafakulov, 2013; Lhuillier et al. 2018; Luneau et al. 2014), and, more recently, local archaeologists under the direction of K. Rakhimov (Institute of Archaeology of Uzbekistan). These excavations have documented the remains of an urban center and a large necropolis covering an area of approximately 50 hectares. The urban area consisted of a fortified enclosure or citadel, which contained various habitats and one monumental building (referred as a "palace"). Another

monumental building (called a “temple”), along with residential and craft areas, were identified surrounding the citadel. Multiple areas of the necropolis are located to the south of the urban area.

The archaeological material recovered during these excavations has made it possible to date the occupation of the Jarkutan site to the Late and Final Bronze Age, approximately between 2100 and 1400 BCE. Additionally, in the “citadel” area only, evidence suggests occupation during the Early Iron Age, between 1250 and 1000 BCE, according to the available data (Görsdorff, Huff 2001, Bendezu-Sarmiento, Mustafakulov 2013). A total of 23 fragments from this site, referred to as JKT for the palaeomagnetic analysis, have been selected for study. the ceramic samples analised correspond to Bronze Age vessels recovered in the excavations conducted during the Soviet era. These were sampled in 2013 by the Spanish-Uzbek IPAEB team at the Termez Museum to conduct archaeometry analyses. Most samples consist of fine ware originating from the necropolis, although in some cases, the precise depositional context may remain uncertain. The chronologies assigned to the ceramic pieces are based on their typology and are classified into two chronological periods: from 2000 BCE to 1700 BCE (Late Bronze Age) and from 1700 BCE to 1400 BCE (Final Bronze Age).

The second archaeological site, Molali Tepe, is located on a river terrace of the Kizylzhar River, a tributary of the Surkhan Darya river (Fig. 1). Discovered in 1970 by the Expedition of Art Study of Uzbekistan, led by G.A. Pugachenkova (Pugachenkova 1972), the site was initially excavated in 1975 by S. Sagullaev and was attributed to one of the later phases of the Sapalli culture, which was called the 'Molali phase' (Sagdullaev, 1978). In 2012-2013, an Uzbek-German team resumed the archaeological work under the

direction of N. Boroffka from the German Archaeological Institute and L.M. Sverchkov from the Institute of Fine Arts of the Academy of Sciences of Uzbekistan (Sverchkov and Boroffka 2015). Both the older and more recent excavations revealed the existence of buildings comprising multiple rooms, as well as two kilns located beyond the residential area. The most recent fieldworks identified three successive occupation phases, with radiocarbon dating indicating that the settlement was occupied between 1600 and 1400 BCE (Sverchkov and Boroffka, 2015). A total of 32 fragments, referred to as MOL, from the excavations performed at Molali Tepe in 2012 have been analyzed in this study. They consist of fine ware ceramics, whose pastes have been previously characterized to gain insight into their chemical, mineralogical, and petrographic composition. Wheel-fashioned fine ware was identified as locally produced, while the coarse and shell-tempered cooking pots have a local or regional origin. The pieces were contextualized based on morphological characteristics and comparative study with other contemporary sites (Luneau et al., 2022). The results demonstrate a high degree of similarity in the raw clay materials and technological processes used in the preparation of the fine wares pastes, in contrast to the greater compositional variability observed in coarse wares.

The third site, Kuchuk Tepe, was excavated between 1961 and 1969, and again in 1977-1978 under the direction of L.I.'Al'baum (Askarov and'Al'baum, 1979). Four successive phases of occupation were identified, corresponding to the full periodization of the Iron Age, during which the settlement gradually expanded eastwards. The excavations documented a small settlement, less than 1 ha in size, consisting of a citadel built on an adobe platform. At present, the citadel is the only excavated area of the site. It consists of a walled area that was progressively enlarged from 60 to 250 m² through the addition of new rooms and the extension of the surrounding wall to the east. The samples studied in

this study were recovered during a surface survey carried out by the Uzbek-Spanish IPAEB team in 2013. In the absence of information on the archaeological contexts, the proposed dates are based on the morphological characteristics of the vessels and comparisons with previously published material from the site (Askarov and'Al'baum, 1979; Lhuillier, 2013; Lyonnet, 1997). A total of 16 ceramic fragments from Kuchuk Tepe, labelled as TRZ, were thoroughly analyzed in this study. These consist of fine ware and have been classified into two distinct temporal groups according to typo-chronological criteria: one spanning from 1000 to 400 BCE, and another from 500 to 300 BCE.

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